

TUNING FRACTAL ANTENNAS AND FRACTAL RESONATORS

RELATION TO PREVIOUSLY FILED PATENT APPLICATION

5 This application is a continuation-in-part application of applicant's pending patent application serial no. 08/512,954 entitled FRACTAL ANTENNAS AND FRACTAL RESONATORS, filed on August 9, 1995.

FIELD OF THE INVENTION

10 The present invention relates to antennas and resonators, and more specifically to tuning non-Euclidian antennas and non-Euclidian resonators.

BACKGROUND OF THE INVENTION

15 Antenna are used to radiate and/or receive typically electromagnetic signals, preferably with antenna gain, directivity, and efficiency. Practical antenna design traditionally involves trade-offs between various
20 parameters, including antenna gain, size, efficiency, and bandwidth.

Antenna design has historically been dominated by Euclidean geometry. In such designs, the closed antenna
25 area is directly proportional to the antenna perimeter. For example, if one doubles the length of an Euclidean square (or "quad") antenna, the enclosed area of the antenna quadruples. Classical antenna design has dealt with planes, circles, triangles, squares, ellipses,
30 rectangles, hemispheres, paraboloids, and the like, (as well as lines). Similarly, resonators, typically capacitors ("C") coupled in series and/or parallel with inductors ("L"), traditionally are implemented with Euclidian inductors.

35 With respect to antennas, prior art design philosophy has been to pick a Euclidean geometric construction, e.g., a

quad, and to explore its radiation characteristics,
especially with emphasis on frequency resonance and power
patterns. The unfortunate result is that antenna design
has far too long concentrated on the ease of antenna
5 construction, rather than on the underlying
electromagnetics.

Many prior art antennas are based upon closed-loop or
island shapes. Experience has long demonstrated that
10 small sized antennas, including loops, do not work well,
one reason being that radiation resistance ("R")
decreases sharply when the antenna size is shortened. A
small sized loop, or even a short dipole, will exhibit a
radiation pattern of $1/2\lambda$ and $1/4\lambda$, respectively, if the
15 radiation resistance R is not swamped by substantially
larger ohmic ("O") losses. Ohmic losses can be minimized
using impedance matching networks, which can be expensive
and difficult to use. But although even impedance
matched small loop antennas can exhibit 50% to 85%
20 efficiencies, their bandwidth is inherently narrow, with
very high Q, e.g., $Q > 50$. As used herein, Q is defined as
(transmitted or received frequency)/(3 dB bandwidth).

As noted, it is well known experimentally that radiation
25 resistance R drops rapidly with small area Euclidean
antennas. However, the theoretical basis is not
generally known, and any present understanding (or
misunderstanding) appears to stem from research by J.
Kraus, noted in Antennas (Ed. 1), McGraw Hill, New York
30 (1950), in which a circular loop antenna with uniform
current was examined. Kraus' loop exhibited a gain with
a surprising limit of 1.8 dB over an isotropic radiator
as loop area falls below that of a loop having a 1λ -
squared aperture. For small loops of area $A < \lambda^2/100$,
35 radiation resistance R was given by:

$$R = K \left(\frac{A}{\lambda^2} \right)^2$$

where K is a constant, A is the enclosed area of the loop, and λ is wavelength. Unfortunately, radiation resistance R can all too readily be less than 1 Ω for a small loop antenna.

5

From his circular loop research Kraus generalized that calculations could be defined by antenna area rather than antenna perimeter, and that his analysis should be correct for small loops of any geometric shape. Kraus' early research and conclusions that small-sized antennas will exhibit a relatively large ohmic resistance O and a relatively small radiation resistance R, such that resultant low efficiency defeats the use of the small antenna have been widely accepted. In fact, some researchers have actually proposed reducing ohmic resistance O to 0 Ω by constructing small antennas from superconducting material, to promote efficiency.

As noted, prior art antenna and resonator design has traditionally concentrated on geometry that is Euclidean. However, one non-Euclidian geometry is fractal geometry. Fractal geometry may be grouped into random fractals, which are also termed chaotic or Brownian fractals and include a random noise components, such as depicted in Figure 3, or deterministic fractals such as shown in Figure 1C.

In deterministic fractal geometry, a self-similar structure results from the repetition of a design or motif (or "generator"), on a series of different size scales. One well known treatise in this field is Fractals, Endlessly Repeated Geometrical Figures, by Hans Lauwerier, Princeton University Press (1991), which treatise applicant refers to and incorporates herein by reference.

Figures 1A-2D depict the development of some elementary forms of fractals. In Figure 1A, a base element 10 is shown as a straight line, although a curve could instead be used. In Figure 1B, a so-called Koch fractal motif or generator 20-1, here a triangle, is inserted into base element 10, to form a first order iteration ("N") design, e.g., N=1. In Figure 1C, a second order N=2 iteration design results from replicating the triangle motif 20-1 into each segment of Figure 1B, but where the 20-1' version has been differently scaled, here reduced in size. As noted in the Lauwerier treatise, in its replication, the motif may be rotated, translated, scaled in dimension, or a combination of any of these characteristics. Thus, as used herein, second order of iteration or N=2 means the fundamental motif has been replicated, after rotation, translation, scaling (or a combination of each) into the first order iteration pattern. A higher order, e.g., N=3, iteration means a third fractal pattern has been generated by including yet another rotation, translation, and/or scaling of the first order motif.

In Figure 1D, a portion of Figure 1C has been subjected to a further iteration (N=3) in which scaled-down versions of the triangle motif 20-1 have been inserted into each segment of the left half of Figure 1C. Figures 2A-2C follow what has been described with respect to Figures 1A-1C, except that a rectangular motif 20-2 has been adopted. Figure 2D shows a pattern in which a portion of the left-hand side is an N=3 iteration of the 20-2 rectangle motif, and in which the center portion of the figure now includes another motif, here a 20-1 type triangle motif, and in which the right-hand side of the figure remains an N=2 iteration.

Traditionally, non-Euclidean designs including random fractals have been understood to exhibit antiresonance

characteristics with mechanical vibrations. It is known in the art to attempt to use non-Euclidean random designs at lower frequency regimes to absorb, or at least not reflect sound due to the antiresonance characteristics.

5 For example, M. Schroeder in Fractals, Chaos, Power Laws (1992), W. H. Freeman, New York discloses the use of presumably random or chaotic fractals in designing sound blocking diffusers for recording studios and auditoriums.

10 Experimentation with non-Euclidean structures has also been undertaken with respect to electromagnetic waves, including radio antennas. In one experiment, Y. Kim and D. Jaggard in The Fractal Random Array, Proc. IEEE 74, 1278-1280 (1986) spread-out antenna elements in a sparse
15 microwave array, to minimize sidelobe energy without having to use an excessive number of elements. But Kim and Jaggard did not apply a fractal condition to the antenna elements, and test results were not necessarily better than any other techniques, including a totally
20 random spreading of antenna elements. More significantly, the resultant array was not smaller than a conventional Euclidean design.

Prior art spiral antennas, cone antennas, and V-shaped
25 antennas may be considered as a continuous, deterministic first order fractal, whose motif continuously expands as distance increases from a central point. A log-periodic antenna may be considered a type of continuous fractal in that it is fabricated from a radially expanding
30 structure. However, log periodic antennas do not utilize the antenna perimeter for radiation, but instead rely upon an arc-like opening angle in the antenna geometry. Such opening angle is an angle that defines the size-scale of the log-periodic structure, which structure is
35 proportional to the distance from the antenna center multiplied by the opening angle. Further, known log-periodic antennas are not necessarily smaller than

conventional driven element-parasitic element antenna designs of similar gain.

Unintentionally, first order fractals have been used to distort the shape of dipole and vertical antennas to increase gain, the shapes being defined as a Brownian-type of chaotic fractals. See F. Landstorfer and R. Sacher, Optimisation of Wire Antennas, J. Wiley, New York (1985). Figure 3 depicts three bent-vertical antennas developed by Landstorfer and Sacher through trial and error, the plots showing the actual vertical antennas as a function of x-axis and y-axis coordinates that are a function of wavelength. The "EF" and "BF" nomenclature in Figure 3 refer respectively to end-fire and back-fire radiation patterns of the resultant bent-vertical antennas.

First order fractals have also been used to reduce horn-type antenna geometry, in which a double-ridge horn configuration is used to decrease resonant frequency. See J. Kraus in Antennas, McGraw Hill, New York (1985). The use of rectangular, box-like, and triangular shapes as impedance-matching loading elements to shorten antenna element dimensions is also known in the art.

Whether intentional or not, such prior art attempts to use a quasi-fractal or fractal motif in an antenna employ at best a first order iteration fractal. By first iteration it is meant that one Euclidian structure is loaded with another Euclidean structure in a repetitive fashion, using the same size for repetition. Figure 1C, for example, is not first order because the 20-1' triangles have been shrunk with respect to the size of the first motif 20-1.

Prior art antenna design does not attempt to exploit multiple scale self-similarity of real fractals. This is

hardly surprising in view of the accepted conventional wisdom that because such antennas would be anti-resonators, and/or if suitably shrunken would exhibit so small a radiation resistance R , that the substantially higher ohmic losses O would result in too low an antenna efficiency for any practical use. Further, it is probably not possible to mathematically predict such an antenna design, and high order iteration fractal antennas would be increasingly difficult to fabricate and erect, in practice.

Figures 4A and 4B depict respective prior art series and parallel type resonator configurations, comprising capacitors C and Euclidean inductors L . In the series configuration of Figure 4A, a notch-filter characteristic is presented in that the impedance from port A to port B is high except at frequencies approaching resonance, determined by $1/\sqrt{LC}$.

In the distributed parallel configuration of Figure 4B, a low-pass filter characteristic is created in that at frequencies below resonance, there is a relatively low impedance path from port A to port B, but at frequencies greater than resonant frequency, signals at port A are shunted to ground (e.g., common terminals of capacitors C), and a high impedance path is presented between port A and port B. Of course, a single parallel LC configuration may also be created by removing (e.g., short-circuiting) the rightmost inductor L and right two capacitors C , in which case port B would be located at the bottom end of the leftmost capacitor C .

In Figures 4A and 4B, inductors L are Euclidean in that increasing the effective area captured by the inductors increases with increasing geometry of the inductors, e.g., more or larger inductive windings or, if not cylindrical, traces comprising inductance. In such prior

art configurations as Figures 4A and 4B, the presence of Euclidean inductors L ensures a predictable relationship between L, C and frequencies of resonance.

5 Applicant's above-noted FRACTAL ANTENNA AND FRACTAL
RESONATORS patent application provides a design
methodology that can produce smaller-scale antennas that
exhibit at least as much gain, directivity, and
efficiency as larger Euclidean counterparts. Such design
10 approach should exploit the multiple scale self-
similarity of real fractals, including $N \geq 2$ iteration
order fractals. Further, as respects resonators, said
application discloses a non-Euclidean resonator whose
presence in a resonating configuration can create
15 frequencies of resonance beyond those normally presented
in series and/or parallel LC configurations.

However, there is a need for a simple mechanism to tune
and/or otherwise adjust such antennas and resonators.

20 The present invention provides such mechanisms.

SUMMARY OF THE INVENTION

The present invention tunes fractal antenna systems and
25 resonator systems, preferably designed according to
applicant's above-reference patent application, by
placing an active (or driven) fractal antenna or
resonator a distance Δ from a second conductor. Such
disposition of the antenna and second conductor
30 advantageously lowers resonant frequencies and widens
bandwidth for the fractal antenna. In some embodiments,
the fractal antenna and second conductor are non-coplanar
and λ is the separation distance therebetween, preferably
 $\leq 0.05\lambda$ for the frequency of interest ($1/\lambda$). In other
35 embodiments, the fractal antenna and second conductive
element may be planar, in which case λ a separation
distance, measured on the common plane.

The second conductor may in fact be a second fractal antenna of like or unlike configuration as the active antenna. Varying the distance Δ tunes the active antenna and thus the overall system. Further, if the second
5 element, preferably a fractal antenna, is angularly rotated relative to the active antenna, resonant frequencies of the active antenna may be varied.

Providing a cut in the fractal antenna results in new and
10 different resonant nodes, including resonant nodes having perimeter compression parameters, defined below, ranging from about three to ten. If desired, a portion of a fractal antenna may be cutaway and removed so as to tune the antenna by increasing resonance(s).

15 Tunable fractal antenna systems need not be planar, according to the present invention. Fabricating a fractal antenna around a form such as a torroid ring, or forming the fractal antenna on a flexible substrate that
20 is curved about itself results in field self-proximity that produces resonant frequency shifts. A fractal antenna and a conductive element may each be formed as a curved surface or even as a torroid-shape, and placed in sufficiently close proximity to each other to provide a
25 useful tuning and system characteristic altering mechanism.

In the various embodiments, more than two elements may be used, and tuning may be accomplished by varying one or
30 more of the parameters associated with one or more elements.

Preferably fractal antennas and resonators so tuned are designed according to applicant's above-referenced patent
35 application, which provides an antenna having at least one element whose shape, at least in part, is substantially a deterministic fractal of iteration order

5 N≥2. Using fractal geometry, the antenna element has a self-similar structure resulting from the repetition of a design or motif (or "generator") that is replicated using rotation, and/or translation, and/or scaling. The fractal element will have x-axis, y-axis coordinates for a next iteration N+1 defined by $x_{N+1} = f(x_N, y_N)$ and $y_{N+1} = g(x_N, y_N)$, where x_N, y_N define coordinates for a preceding iteration, and where $f(x,y)$ and $g(x,y)$ are functions defining the fractal motif and behavior.

10 In contrast to Euclidean geometric antenna design, applicant's deterministic fractal antenna elements have a perimeter that is not directly proportional to area. For a given perimeter dimension, the enclosed area of a multi-iteration fractal will always be as small or smaller than the area of a corresponding conventional Euclidean antenna.

20 A fractal antenna has a fractal ratio limit dimension D given by $\log(L)/\log(r)$, where L and r are one-dimensional antenna element lengths before and after fractalization, respectively.

25 As used with the present invention, a fractal antenna perimeter compression parameter (PC) is defined as:

$$PC = \frac{\text{full-sized antenna element length}}{\text{fractal-reduced antenna element length}}$$

where:

$$PC = A \cdot \log[N(D + C)]$$

in which A and C are constant coefficients for a given fractal motif, N is an iteration number, and D is the fractal dimension, defined above.

30 Radiation resistance (R) of a fractal antenna decreases as a small power of the perimeter compression (PC), with a fractal loop or island always exhibiting a

substantially higher radiation resistance than a small Euclidean loop antenna of equal size. In the present invention, deterministic fractals are used wherein A and C have large values, and thus provide the greatest and most rapid element-size shrinkage. A fractal antenna according to the present invention will exhibit an increased effective wavelength.

The number of resonant nodes of a fractal loop-shaped antenna according to the present invention increases as the iteration number N and is at least as large as the number of resonant nodes of an Euclidean island with the same area. Further, resonant frequencies of a fractal antenna include frequencies that are not harmonically related.

A fractal antenna according to the present invention is smaller than its Euclidean counterpart but provides at least as much gain and frequencies of resonance and provides essentially a 50Ω termination impedance at its lowest resonant frequency. Further, the fractal antenna exhibits non-harmonically frequencies of resonance, a low Q and resultant good bandwidth, acceptable standing wave ratio ("SWR"), a radiation impedance that is frequency dependent, and high efficiencies. Fractal inductors of first or higher iteration order may also be provided in LC resonators, to provide additional resonant frequencies including non-harmonically related frequencies.

Other features and advantages of the invention will appear from the following description in which the preferred embodiments have been set forth in detail, in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1A depicts a base element for an antenna or an inductor, according to the prior art;

FIGURE 1B depicts a triangular-shaped Koch fractal motif, according to the prior art;

FIGURE 1C depicts a second-iteration fractal using the motif of Figure 1B, according to the prior art;

FIGURE 1D depicts a third-iteration fractal using the motif of Figure 1B, according to the prior art;

FIGURE 2A depicts a base element for an antenna or an inductor, according to the prior art;

FIGURE 2B depicts a rectangular-shaped Minkowski fractal motif, according to the prior art;

FIGURE 2C depicts a second-iteration fractal using the motif of Figure 2B, according to the prior art;

FIGURE 2D depicts a fractal configuration including a third-order using the motif of Figure 2B, as well as the motif of Figure 1B, according to the prior art;

FIGURE 3 depicts bent-vertical chaotic fractal antennas, according to the prior art;

FIGURE 4A depicts a series L-C resonator, according to the prior art;

FIGURE 4B depicts a distributed parallel L-C resonator, according to the prior art;

FIGURE 5A depicts an Euclidean quad antenna system, according to the prior art;

FIGURE 5B depicts a second-order Minkowski island fractal quad antenna, according to the present invention;

FIGURE 6 depicts an ELNEC-generated free-space radiation pattern for an MI-2 fractal antenna, according to the present invention;

- 5 FIGURE 7A depicts a Cantor-comb fractal dipole antenna, according to the present invention;

FIGURE 7B depicts a torn square fractal quad antenna, according to the present invention;

10

FIGURE 7C-1 depicts a second iteration Minkowski (MI-2) printed circuit fractal antenna, according to the present invention;

- 15 FIGURE 7C-2 depicts a second iteration Minkowski (MI-2) slot fractal antenna, according to the present invention;

FIGURE 7D depicts a deterministic dendrite fractal vertical antenna, according to the present invention;

20

FIGURE 7E depicts a third iteration Minkowski island (MI-3) fractal quad antenna, according to the present invention;

- 25 FIGURE 7F depicts a second iteration Koch fractal dipole, according to the present invention;

FIGURE 7G depicts a third iteration dipole, according to the present invention;

30

FIGURE 7H depicts a second iteration Minkowski fractal dipole, according to the present invention;

- 35 FIGURE 7I depicts a third iteration multi-fractal dipole, according to the present invention;

FIGURE 8A depicts a generic system in which a passive or active electronic system communicates using a fractal antenna, according to the present invention;

5 FIGURE 8B depicts a communication system in which several fractal antennas are electronically selected for best performance, according to the present invention;

10 FIGURE 8C depicts a communication system in which electronically steerable arrays of fractal antennas are electronically selected for best performance, according to the present invention;

15 FIGURE 9A depicts fractal antenna gain as a function of iteration order N , according to the present invention;

20 FIGURE 9B depicts perimeter compression PC as a function of iteration order N for fractal antennas, according to the present invention;

FIGURE 10A depicts a fractal inductor for use in a fractal resonator, according to the present invention;

25 FIGURE 10B depicts a credit card sized security device utilizing a fractal resonator, according to the present invention;

30 FIGURE 11A depicts an embodiment in which a fractal antenna is spaced-apart a distance Δ from a conductor element to vary resonant properties and radiation characteristics of the antenna, according to the present invention;

35 FIGURE 11B depicts an embodiment in which a fractal antenna is coplanar with a ground plane and is spaced-apart a distance Δ' from a coplanar passive parasitic element to vary resonant properties and radiation

characteristics of the antenna, according to the present invention;

5 FIGURE 12A depicts spacing-apart first and second fractal antennas a distance Δ to decrease resonance and create additional resonant frequencies for the active or driven antenna, according to the present invention;

10 FIGURE 12B depicts relative angular rotation between spaced-apart first and second fractal antennas Δ to vary resonant frequencies of the active or driven antenna, according to the present invention;

15 FIGURE 13A depicts cutting a fractal antenna or resonator to create different resonant nodes and to alter perimeter compression, according to the present invention;

20 FIGURE 13B depicts forming a non-planar fractal antenna or resonator on a flexible substrate that is curved to shift resonant frequency, apparently due to self-proximity electromagnetic fields, according to the present invention;

25 FIGURE 13C depicts forming a fractal antenna or resonator on a curved torroidal form to shift resonant frequency, apparently due to self-proximity electromagnetic fields, according to the present invention;

30 FIGURE 14A depicts forming a fractal antenna or resonator in which the conductive element is not attached to the system coaxial or other feedline, according to the present invention;

35 FIGURE 14B depicts a system similar to Figure 14A, but demonstrates that the driven fractal antenna may be coupled to the system coaxial or other feedline at any

point along the antenna, according to the present invention;

FIGURE 14C depicts an embodiment in which a supplemental
5 ground plane is disposed adjacent a portion of the driven
fractal antenna and conductive element, forming a
sandwich-like system, according to the present invention;

FIGURE 14D depicts an embodiment in which a fractal
10 antenna system is tuned by cutting away a portion of the
driven antenna, according to the present invention;

FIGURE 15 depicts a communication system similar to that
of Figure 8A, in which several fractal antennas are
15 tunable and are electronically selected for best
performance, according to the present invention.

20 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In overview, the present invention provides an antenna
having at least one element whose shape, at least is
part, is substantially a fractal of iteration order $N \geq 2$.
The resultant antenna is smaller than its Euclidean
25 counterpart, provides a 50Ω termination impedance,
exhibits at least as much gain and more frequencies of
resonance than its Euclidean counterpart, including non-
harmonically related frequencies of resonance, exhibits a
low Q and resultant good bandwidth, acceptable SWR, a
30 radiation impedance that is frequency dependent, and high
efficiencies.

In contrast to Euclidean geometric antenna design,
fractal antenna elements according to the present
35 invention have a perimeter that is not directly
proportional to area. For a given perimeter dimension,

the enclosed area of a multi-iteration fractal area will always be at least as small as any Euclidean area.

Using fractal geometry, the antenna element has a self-similar structure resulting from the repetition of a design or motif (or "generator"), which motif is replicated using rotation, translation, and/or scaling (or any combination thereof). The fractal portion of the element has x-axis, y-axis coordinates for a next iteration N+1 defined by $x_{N+1} = f(x_N, y_N)$ and $y_{N+1} = g(x_N, y_N)$, where x_N, y_N are coordinates of a preceding iteration, and where $f(x,y)$ and $g(x,y)$ are functions defining the fractal motif and behavior.

For example, fractals of the Julia set may be represented by the form:

$$\begin{aligned}x_{N+1} &= x_N^2 - y_N^2 + a \\y_{N+1} &= 2x_N y_N + b\end{aligned}$$

In complex notation, the above may be represented as:

$$z_{N+1} = z_N^2 + c$$

Although it is apparent that fractals can comprise a wide variety of forms for functions $f(x,y)$ and $g(x,y)$, it is the iterative nature and the direct relation between structure or morphology on different size scales that uniquely distinguish $f(x,y)$ and $g(x,y)$ from non-fractal forms. Many references including the Lauwerier treatise set forth equations appropriate for $f(x,y)$ and $g(x,y)$.

Iteration (N) is defined as the application of a fractal motif over one size scale. Thus, the repetition of a single size scale of a motif is not a fractal as that term is used herein. Multi-fractals may of course be implemented, in which a motif is changed for different iterations, but eventually at least one motif is repeated in another iteration.

An overall appreciation of the present invention may be obtained by comparing Figures 5A and 5B. Figure 5A shows a conventional Euclidean quad antenna 5 having a driven element 10 whose four sides are each 0.25λ long, for a total perimeter of 1λ , where λ is the frequency of interest.

Euclidean element 10 has an impedance of perhaps $130\ \Omega$, which impedance decreases if a parasitic quad element 20 is spaced apart on a boom 30 by a distance B of 0.1λ to 0.25λ . Parasitic element 20 is also sized $S=0.25\lambda$ on a side, and its presence can improve directivity of the resultant two-element quad antenna. Element 10 is depicted in Figure 5A with heavier lines than element 20, solely to avoid confusion in understanding the figure. Non-conductive spreaders 40 are used to help hold element 10 together and element 20 together.

Because of the relatively large drive impedance, driven element 10 is coupled to an impedance matching network or device 60, whose output impedance is approximately $50\ \Omega$. A typically $50\ \Omega$ coaxial cable 50 couples device 60 to a transceiver 70 or other active or passive electronic equipment 70.

As used herein, the term transceiver shall mean a piece of electronic equipment that can transmit, receive, or transmit and receive an electromagnetic signal via an antenna, such as the quad antenna shown in Figure 5A or 5B. As such, the term transceiver includes without limitation a transmitter, a receiver, a transmitter-receiver, a cellular telephone, a wireless telephone, a pager, a wireless computer local area network ("LAN") communicator, a passive resonant unit used by stores as part of an anti-theft system in which transceiver 70 contains a resonant circuit that is blown or not-blown by an electronic signal at time of purchase of the item to

which transceiver 70 is affixed, resonant sensors and transponders, and the like.

Further, since antennas according to the present invention can receive incoming radiation and coupled the same as alternating current into a cable, it will be appreciated that fractal antennas may be used to intercept incoming light radiation and to provide a corresponding alternating current. For example, a photocell antenna defining a fractal, or indeed a plurality or array of fractals, would be expected to output more current in response to incoming light than would a photocell of the same overall array size. Figure 5B depicts a fractal quad antenna 95, designed to resonant at the same frequency as the larger prior art antenna 5 shown in Figure 5A. Driven element 100 is seen to be a second order fractal, here a so-called Minkowski island fractal, although any of numerous other fractal configurations could instead be used, including without limitation, Koch, torn square, Mandelbrot, Caley tree, monkey's swing, Sierpinski gasket, and Cantor gasket geometry.

If one were to measure to the amount of conductive wire or conductive trace comprising the perimeter of element 40, it would be perhaps 40% greater than the 1.0λ for the Euclidean quad of Figure 5A. However, for fractal antenna 95, the physical straight length of one element side KS will be substantially smaller, and for the N=2 fractal antenna shown in Figure 5B, $KS \approx 0.13\lambda$ (in air), compared with $K \approx 0.25\lambda$ for prior art antenna 5.

However, although the actual perimeter length of element 100 is greater than the 1λ perimeter of prior art element 10, the area within antenna element 100 is substantially less than the S^2 area of prior art element 10. As noted, this area independence from perimeter is a characteristic

of a deterministic fractal. Boom length B for antenna 95 will be slightly different from length B for prior art antenna 5 shown in Figure 4A. In Figure 5B, a parasitic element 120, which preferably is similar to driven element 100 but need not be, may be attached to boom 130. For ease of illustration Figure 5B does not depict non-conductive spreaders, such as spreaders 40 shown in Figure 4A, which help hold element 100 together and element 120 together. Further, for ease of understanding the figure, element 10 is drawn with heavier lines than element 120, to avoid confusion in the portion of the figure in which elements 100 and 120 appear overlapped.

An impedance matching device 60 is advantageously unnecessary for the fractal antenna of Figure 5B, as the driving impedance of element 100 is about 50Ω , e.g., a perfect match for cable 50 if reflector element 120 is absent, and about 35Ω , still an acceptable impedance match for cable 50, if element 120 is present. Antenna 95 may be fed by cable 50 essentially anywhere in element 100, e.g., including locations X, Y, Z, among others, with no substantial change in the termination impedance. With cable 50 connected as shown, antenna 95 will exhibit horizontal polarization. If vertical polarization is desired, connection may be made as shown by cable 50'. If desired, cables 50 and 50' may both be present, and an electronic switching device 75 at the antenna end of these cables can short-out one of the cables. If cable 50 is shorted out at the antenna, vertical polarization results, and if instead cable 50' is shorted out at the antenna, horizontal polarization results.

As shown by Table 3 herein, fractal quad 95 exhibits about 1.5 dB gain relative to Euclidean quad 10. Thus, transmitting power output by transceiver 70 may be cut by perhaps 40% and yet the system of Figure 5B will still perform no worse than the prior art system of Figure 5A.

Further, as shown by Table 1, the fractal antenna of Figure 5B exhibits more resonance frequencies than the antenna of Figure 5B, and also exhibits some resonant frequencies that are not harmonically related to each other. As shown by Table 3, antenna 95 has efficiency exceeding about 92% and exhibits an excellent SWR of about 1.2:1. As shown by Table 5, applicant's fractal quad antenna exhibits a relatively low value of Q. This result is surprising in view of conventional prior art wisdom to the effect that small loop antennas will exhibit high Q.

In short, that fractal quad 95 works at all is surprising in view of the prior art (mis)understanding as to the nature of radiation resistance R and ohmic losses O. Indeed, the prior art would predict that because the fractal antenna of Figure 5B is smaller than the conventional antenna of Figure 5A, efficiency would suffer due to an anticipated decrease in radiation resistance R. Further, it would have been expected that Q would be unduly high for a fractal quad antenna.

Figure 6 is an ELNEC-generated free-space radiation pattern for a second-iteration Minkowski fractal antenna, an antenna similar to what is shown in Figure 5B with the parasitic element 120 omitted. The frequency of interest was 42.3 MHz, and a 1.5:1 SWR was used. In Figure 6, the outer ring represents 2.091 dBi, and a maximum gain of 2.091 dBi. (ELNEC is a graphics/PC version of MININEC, which is a PC version of NEC.) In practice, however, the data shown in Figure 6 were conservative in that a gain of 4.8 dB above an isotropic reference radiator was actually obtained. The error in the gain figures associated with Figure 6 presumably is due to roundoff and other limitations inherent in the ELNEC program. Nonetheless, Figure 6 is believed to accurately depict the relative gain radiation pattern of a single element

Minkowski (MI-2) fractal quad according to the present invention.

Figure 7A depicts a third iteration Cantor-comb fractal dipole antenna, according to the present invention. Generation of a Cantor-comb involves trisecting a basic shape, e.g., a rectangle, and providing a rectangle of one-third of the basic shape on the ends of the basic shape. The new smaller rectangles are then trisected, and the process repeated. Figure 7B is modelled after the Lauwerier treatise, and depicts a single element torn-sheet fractal quad antenna.

Figure 7C-1 depicts a printed circuit antenna, in which the antenna is fabricated using printed circuit or semiconductor fabrication techniques. For ease of understanding, the etched-away non-conductive portion of the printed circuit board 150 is shown cross-hatched, and the copper or other conductive traces 170 are shown without cross-hatching.

Applicant notes that while various corners of the Minkowski rectangle motif may appear to be touching in this and perhaps other figures herein, in fact no touching occurs. Further, it is understood that it suffices if an element according to the present invention is substantially a fractal. By this it is meant that a deviation of less than perhaps 10% from a perfectly drawn and implemented fractal will still provide adequate fractal-like performance, based upon actual measurements conducted by applicant.

The substrate 150 is covered by a conductive layer of material 170 that is etched away or otherwise removed in areas other than the fractal design, to expose the substrate 150. The remaining conductive trace portion 170 defines a fractal antenna, a second iteration

Minkowski slot antenna in Figure 7C. Substrate 150 may be a silicon wafer, a rigid or a flexible plastic-like material, perhaps MylarTM material, or the non-conductive portion of a printed circuit board. Overlayer 170 may be deposited doped polysilicon for a semiconductor substrate 150, or copper for a printed circuit board substrate.

Figure 7C-2 depicts a slot antenna version of what was shown in Figure 7C-2, wherein the conductive portion 170 (shown cross-hatched in Figure 7C-2) surrounds and defines a fractal-shape of non-conductive substrate 150. Electrical connection to the slot antenna is made with a coaxial or other cable 50, whose inner and outer conductors make contact as shown.

In Figures 7C-1 and 7C-2, the substrate or plastic-like material in such constructions can contribute a dielectric effect that may alter somewhat the performance of a fractal antenna by reducing resonant frequency, which increases perimeter compression PC.

Those skilled in the art will appreciate that by virtue of the relatively large amount of conducting material (as contrasted to a thin wire), antenna efficiency is promoted in a slot configuration. Of course a printed circuit board or substrate-type construction could be used to implement a non-slot fractal antenna, e.g, in which the fractal motif is fabricated as a conductive trace and the remainder of the conductive material is etched away or otherwise removed. Thus, in Figure 7C, if the cross-hatched surface now represents non-conductive material, and the non-cross hatched material represents conductive material, a printed circuit board or substrate-implemented wire-type fractal antenna results.

Printed circuit board and/or substrate-implemented fractal antennas are especially useful at frequencies of

80 MHz or higher, whereat fractal dimensions indeed become small. A 2 M MI-3 fractal antenna (e.g., Figure 7E) will measure about 5.5" (14 cm) on a side KS, and an MI-2 fractal antenna (e.g., Figure 5B) will about 7"

5 (17.5 cm) per side KS. As will be seen from Figure 8A, an MI-3 antenna suffers a slight loss in gain relative to an MI-2 antenna, but offers substantial size reduction.

Applicant has fabricated an MI-2 Minkowski island fractal
10 antenna for operation in the 850-900 MHz cellular telephone band. The antenna was fabricated on a printed circuit board and measured about 1.2" (3 cm) on a side KS. The antenna was sufficiently small to fit inside applicant's cellular telephone, and performed as well as
15 if the normal attachable "rubber-ducky" whip antenna were still attached. The antenna was found on the side to obtain desired vertical polarization, but could be fed anywhere on the element with 50 Ω impedance still being inherently present. Applicant also fabricated on a
20 printed circuit board an MI-3 Minkowski island fractal quad, whose side dimension KS was about 0.8" (2 cm), the antenna again being inserted inside the cellular telephone. The MI-3 antenna appeared to work as well as the normal whip antenna, which was not attached. Again,
25 any slight gain loss in going from MI-2 to MI-3 (e.g., perhaps 1 dB loss relative to an MI-0 reference quad, or 3 dB loss relative to an MI-2) is more than offset by the resultant shrinkage in size. At satellite telephone frequencies of 1650 MHz or so, the dimensions would be
30 approximated halved again. Figures 8A, 8B and 8C depict preferred embodiments for such antennas.

Figure 7D depicts a 2 M dendrite deterministic fractal antenna that includes a slight amount of randomness. The
35 vertical arrays of numbers depict wavelengths relative to 0λ , at the lower end of the trunk-like element 200. Eight radial-like elements 210 are disposed at 1.0λ , and

various other elements are disposed vertically in a plane along the length of element 200. The antenna was fabricated using 12 gauge copper wire and was found to exhibit a surprising 20 dBi gain, which is at least 10 dB better than any antenna twice the size of what is shown in Figure 7D. Although superficially the vertical of Figure 7D may appear analogous to a log-periodic antenna, a fractal vertical according to the present invention does not rely upon an opening angle, in stark contrast to prior art log periodic designs.

Figure 7E depicts a third iteration Minkowski island quad antenna (denoted herein as MI-3). The orthogonal line segments associated with the rectangular Minkowski motif make this configuration especially acceptable to numerical study using ELNEC and other numerical tools using moments for estimating power patterns, among other modelling schemes. In testing various fractal antennas, applicant formed the opinion that the right angles present in the Minkowski motif are especially suitable for electromagnetic frequencies.

With respect to the MI-3 fractal of Figure 7E, applicant discovered that the antenna becomes a vertical if the center led of coaxial cable 50 is connected anywhere to the fractal, but the outer coaxial braid-shield is left unconnected at the antenna end. (At the transceiver end, the outer shield is connected to ground.) Not only do fractal antenna islands perform as vertical antennas when the center conductor of cable 50 is attached to but one side of the island and the braid is left ungrounded at the antenna, but resonance frequencies for the antenna so coupled are substantially reduced. For example, a 2" (5 cm) sized MI-3 fractal antenna resonated at 70 MHz when so coupled, which is equivalent to a perimeter compression $PC \approx 20$.

Figure 7F depicts a second iteration Koch fractal dipole, and Figure 7G a third iteration dipole. Figure 7H depicts a second iteration Minkowski fractal dipole, and Figure 7I a third iteration multi-fractal dipole.

5 Depending upon the frequencies of interest, these antennas may be fabricated by bending wire, or by etching or otherwise forming traces on a substrate. Each of these dipoles provides substantially 50 Ω termination impedance to which coaxial cable 50 may be directly
10 coupled without any impedance matching device. It is understood in these figures that the center conductor of cable 50 is attached to one side of the fractal dipole, and the braid outer shield to the other side.

15 Figure 8A depicts a generalized system in which a transceiver 500 is coupled to a fractal antenna system 510 to send electromagnetic radiation 520 and/or receive electromagnetic radiation 540. A second transceiver 600
20 shown equipped with a conventional whip-like vertical antenna 610 also sends electromagnetic energy 630 and/or receives electromagnetic energy 540.

If transceivers 500, 600 are communication devices such as transmitter-receivers, wireless telephones, pagers, or
25 the like, a communications repeating unit such as a satellite 650 and/or a ground base repeater unit 660 coupled to an antenna 670, or indeed to a fractal antenna according to the present invention, may be present.

30 Alternatively, antenna 510 in transceiver 500 could be a passive LC resonator fabricated on an integrated circuit microchip, or other similarly small sized substrate, attached to a valuable item to be protected. Transceiver 600, or indeed unit 660 would then be an electromagnetic
35 transmitter outputting energy at the frequency of resonance, a unit typically located near the cash register checkout area of a store or at an exit.

Depending upon whether fractal antenna-resonator 510 is designed to "blow" (e.g., become open circuit) or to "short" (e.g., become a close circuit) in the transceiver 500 will or will not reflect back electromagnetic energy 540 or 6300 to a receiver associated with transceiver 600. In this fashion, the unauthorized relocation of antenna 510 and/or transceiver 500 can be signalled by transceiver 600.

- 10 Figure 8B depicts a transceiver 500 equipped with a plurality of fractal antennas, here shown as 510A, 510B, 510C coupled by respective cables 50A, 50B, 50C to electronics 600 within unit 500. In the embodiment shown, the antennas are fabricated on a conformal, flexible substrate 150, e.g., MylarTM material or the like, upon which the antennas per se may be implemented by printing fractal patterns using conductive ink, by copper deposition, among other methods including printed circuit board and semiconductor fabrication techniques.
- 15
- 20 A flexible such substrate may be conformed to a rectangular, cylindrical or other shape as necessary.

- In the embodiment of Figure 8B, unit 500 is a handheld transceiver, and antennas 510A, 510B, 510C preferably are fed for vertical polarization, as shown. An electronic circuit 610 is coupled by cables 50A, 50B, 50C to the antennas, and samples incoming signals to discern which fractal antenna, e.g., 510A, 510B, 510C is presently most optimally aligned with the transmitting station, perhaps a unit 600 or 650 or 670 as shown in Figure 8A. This determination may be made by examining signal strength from each of the antennas. An electronic circuit 620 then selects the presently best oriented antenna, and couples such antenna to the input of the receiver and output of the transmitter portion, collectively 630, of unit 500. It is understood that the selection of the best antenna is dynamic and can change as, for example, a
- 25
- 30
- 35

user of 500 perhaps walks about holding the unit, or the transmitting source moves, or due to other changing conditions. In a cellular or a wireless telephone application, the result is more reliable communication, with the advantage that the fractal antennas can be sufficiently small-sized as to fit totally within the casing of unit 500. Further, if a flexible substrate is used, the antennas may be wrapped about portions of the internal casing, as shown.

An additional advantage of the embodiment of Figure 8B is that the user of unit 500 may be physically distanced from the antennas by a greater distance than if a conventional external whip antenna were used. Although medical evidence attempting to link cancer with exposure to electromagnetic radiation from handheld transceivers is still inconclusive, the embodiment of Figure 8B appears to minimize any such risk.

Figure 8C depicts yet another embodiment wherein some or all of the antenna systems 510A, 510B, 510C may include electronically steerable arrays, including arrays of fractal antennas of differing sizes and polarization orientations. Antenna system 510C, for example may include similarly designed fractal antennas, e.g., antenna F-3 and F-4, which are differently oriented from each other. Other antennas within system 510C may be different in design from either of F-3, F-4. Fractal antenna F-1 may be a dipole for example. Leads from the various antennas in system 510C may be coupled to an integrated circuit 690, mounted on substrate 150. Circuit 690 can determine relative optimum choice between the antennas comprising system 510C, and output via cable 50C to electronics 600 associated with the transmitter and/or receiver portion of unit 630.

Another antenna system 510B may include a steerable array of identical fractal antennas, including fractal antenna F-5 and F-6. An integrated circuit 690 is coupled to each of the antennas in the array, and dynamically
5 selects the best antenna for signal strength and coupled such antenna via cable 50B to electronics 600. A third antenna system 510A may be different from or identical to either of system 510B and 510C.

10 Although Figure 8C depicts a unit 500 that may be handheld, unit 500 could in fact be a communications system for use on a desk or a field mountable unit, perhaps unit 660 as shown in Figure 8A.

15 For ease of antenna matching to a transceiver load, resonance of a fractal antenna was defined as a total impedance falling between about 20 Ω to 200 Ω , and the antenna was required to exhibit medium to high Q, e.g., frequency/ Δ frequency. In practice, applicants' various
20 fractal antennas were found to resonate in at least one position of the antenna feedpoint, e.g., the point at which coupling was made to the antenna. Further, multi-iteration fractals according to the present invention were found to resonate at multiple frequencies, including
25 frequencies that were non-harmonically related.

Contrary to conventional wisdom, applicant found that island-shaped fractals (e.g., a closed loop-like configuration) do not exhibit significant drops in
30 radiation resistance R for decreasing antenna size. As described herein, fractal antennas were constructed with dimensions of less than 12" across (30.48 cm) and yet resonated in a desired 60 MHz to 100 MHz frequency band.

35 Applicant further discovered that antenna perimeters do not correspond to lengths that would be anticipated from measured resonant frequencies, with actual lengths being

longer than expected. This increase in element length appears to be a property of fractals as radiators, and not a result of geometric construction. A similar lengthening effect was reported by Pfeiffer when
5 constructing a full-sized quad antenna using a first order fractal, see A. Pfeiffer, The Pfeiffer Quad Antenna System, QST, p. 28-32 (March 1994).

If L is the total initial one-dimensional length of a
10 fractal pre-motif application, and r is the one-dimensional length post-motif application, the resultant fractal dimension D (actually a ratio limit) is:

$$D = \log(L)/\log(r)$$

With reference to Figure 1A, for example, the length of
15 Figure 1A represents L, whereas the sum of the four line segments comprising the Koch fractal of Figure 1B represents r.

Unlike mathematical fractals, fractal antennas are not
20 characterized solely by the ratio D. In practice D is not a good predictor of how much smaller a fractal design antenna may be because D does not incorporate the perimeter lengthening of an antenna radiating element.

25 Because D is not an especially useful predictive parameter in fractal antenna design, a new parameter "perimeter compression" ("PC") shall be used, where:

$$PC = \frac{\text{full-sized antenna element length}}{\text{fractal-reduced antenna element length}}$$

In the above equation, measurements are made at the
30 fractal-resonating element's lowest resonant frequency. Thus, for a full-sized antenna according to the prior art PC=1, while PC=3 represents a fractal antenna according to the present invention, in which an element side has been reduced by a factor of three.

35

Perimeter compression may be empirically represented using the fractal dimension D as follows:

$$PC = A \cdot \log[N(D + C)]$$

where A and C are constant coefficients for a given fractal motif, N is an iteration number, and D is the fractal dimension, defined above.

It is seen that for each fractal, PC becomes asymptotic to a real number and yet does not approach infinity even as the iteration number N becomes very large. Stated differently, the PC of a fractal radiator asymptotically approaches a non-infinite limit in a finite number of fractal iterations. This result is not a representation of a purely geometric fractal.

That some fractals are better resonating elements than other fractals follows because optimized fractal antennas approach their asymptotic PCs in fewer iterations than non-optimized fractal antennas. Thus, better fractals for antennas will have large values for A and C, and will provide the greatest and most rapid element-size shrinkage. Fractal used may be deterministic or chaotic. Deterministic fractals have a motif that replicates at a 100% level on all size scales, whereas chaotic fractals include a random noise component.

Applicant found that radiation resistance of a fractal antenna decreases as a small power of the perimeter compression (PC), with a fractal island always exhibiting a substantially higher radiation resistance than a small Euclidean loop antenna of equal size.

Further, it appears that the number of resonant nodes of a fractal island increase as the iteration number (N) and is always greater than or equal to the number of resonant nodes of an Euclidean island with the same area.

Finally, it appears that a fractal resonator has an increased effective wavelength.

5 The above findings will now be applied to experiments conducted by applicant with fractal resonators shaped into closed-loops or islands. Prior art antenna analysis would predict no resonance points, but as shown below, such is not the case.

10 A Minkowski motif is depicted in Figures 2B-2D, 5B, 7C and 7E. The Minkowski motif selected was a three-sided box (e.g., 20-2 in Figure 2B) placed atop a line segment. The box sides may be any arbitrary length, e.g, perhaps a box height and width of 2 units with the two remaining
15 base sides being of length three units (see Figure 2B). For such a configuration, the fractal dimension D is as follows:

$$D = \frac{\log(L)}{\log(r)} = \frac{\log(12)}{\log(8)} = \frac{1.08}{0.90} = 1.20$$

It will be appreciated that D=1.2 is not especially high when compared to other deterministic fractals.

20

Applying the motif to the line segment may be most simply expressed by a piecewise function f(x) as follows:

$$\begin{aligned} f(x) &= 0 & 0 \leq x \leq \frac{3x_{\max}}{8} \\ f(x) &= \frac{1}{4x_{\max}} & \frac{3x_{\max}}{8} \leq x \leq \frac{5x_{\max}}{8} \\ f(x) &= 0 & \frac{5x_{\max}}{8} \leq x \leq x_{\max} \end{aligned}$$

25 where x_{\max} is the largest continuous value of x on the line segment.

A second iteration may be expressed as $f(x)_2$ relative to the first iteration $f(x)_1$ by:

$$f(x)_2 = f(x)_1 + f(x)$$

where x_{\max} is defined in the above-noted piecewise function. Note that each separate horizontal line segment will have a different lower value of x and x_{\max} . Relevant offsets from zero may be entered as needed, and vertical segments may be "boxed" by 90° rotation and application of the above methodology.

As shown by Figures 5B and 7E, a Minkowski fractal quickly begins to appear like a Moorish design pattern. However, each successive iteration consumes more perimeter, thus reducing the overall length of an orthogonal line segment. Four box or rectangle-like fractals of the same iteration number N may be combined to create a Minkowski fractal island, and a resultant "fractalized" cubical quad.

An ELNEC simulation was used as a guide to far-field power patterns, resonant frequencies, and SWRs of Minkowski Island fractal antennas up to iteration $N=2$. Analysis for $N>2$ was not undertaken due to inadequacies in the test equipment available to applicant.

The following tables summarize applicant's ELNEC simulated fractal antenna designs undertaken to derive lowest frequency resonances and power patterns, to and including iteration $N=2$. All designs were constructed on the x,y axis, and for each iteration the outer length was maintained at 42" (106.7 cm).

Table 1, below, summarizes ELNEC-derived far field radiation patterns for Minkowski island quad antennas for each iteration for the first four resonances. In Table 1, each iteration is designed as MI- N for Minkowski Island of iteration N . Note that the frequency of lowest resonance decreased with the fractal Minkowski Island

antennas, as compared to a prior art quad antenna. Stated differently, for a given resonant frequency, a fractal Minkowski Island antenna will be smaller than a conventional quad antenna.

5

TABLE 1

Antenna	Res. Freq. (MHz)	Gain (dBi)	SWR	PC (for 1st)	Direction
Ref. Quad	76	3.3	2.5	1	Broadside
	144	2.8	5.3	--	Endfire
	220	3.1	5.2	--	Endfire
	294	5.4	4.5	--	Endfire
MI-1	55	2.6	1.1	1.38	Broadside
	101	3.7	1.4	--	Endfire
	142	3.5	5.5	--	Endfire
	198	2.7	3.3	--	Broadside
MI-2	43.2	2.1	1.5	1.79	Broadfire
	85.5	4.3	1.8	--	Endfire
	102	2.7	4.0	--	Endfire
	116	1.4	5.4	--	Broadside

10

15

20

It is apparent from Table 1 that Minkowski island fractal antennas are multi-resonant structures having virtually the same gain as larger, full-sized conventional quad antennas. Gain figures in Table 1 are for "free-space" in the absence of any ground plane, but simulations over a perfect ground at 1λ yielded similar gain results. Understandably, there will be some inaccuracy in the ELNEC results due to round-off and undersampling of pulses, among other factors.

25

30

Table 2 presents the ratio of resonant ELNEC-derived frequencies for the first four resonance nodes referred to in Table 1.

35

TABLE 2

Antenna	SWR	SWR	SWR	SWR
Ref. Quad (MI-0)	1:1	1:1.89	1:2.89	3.86:1
MI-1	1:1	1:1.83	1;2.58	3.6:1
MI-2	1:1	2.02:1	2.41:1	2.74:1

Tables 1 and 2 confirm the shrinking of a fractal-designed antenna, and the increase in the number of resonance points. In the above simulations, the fractal MI-2 antenna exhibited four resonance nodes before the prior art reference quad exhibited its second resonance. Near fields in antennas are very important, as they are combined in multiple-element antennas to achieve high gain arrays. Unfortunately, programming limitations inherent in ELNEC preclude serious near field investigation. However, as described later herein, applicant has designed and constructed several different high gain fractal arrays that exploit the near field.

Applicant fabricated three Minkowski Island fractal antennas from aluminum #8 and/or thinner #12 galvanized groundwire. The antennas were designed so the lowest operating frequency fell close to a desired frequency in the 2 M (144 MHz) amateur radio band to facilitate relative gain measurements using 2 M FM repeater stations. The antennas were mounted for vertical polarization and placed so their center points were the highest practical point above the mounting platform. For gain comparisons, a vertical ground plane having three reference radials, and a reference quad were constructed, using the same sized wire as the fractal antenna being tested. Measurements were made in the receiving mode.

Multi-path reception was minimized by careful placement of the antennas. Low height effects were reduced and free space testing approximated by mounting the antenna test platform at the edge of a third-store window,

affording a 3.5λ height above ground, and line of sight to the repeater, 45 miles (28 km) distant. The antennas were stuck out of the window about 0.8λ from any metallic objects and testing was repeated on five occasions from different windows on the same floor, with test results being consistent within $1/2$ dB for each trial.

Each antenna was attached to a short piece of 9913 50Ω coaxial cable, fed at right angles to the antenna. A 2 M transceiver was coupled with 9913 coaxial cable to two precision attenuators to the antenna under test. The transceiver S-meter was coupled to a volt-ohm meter to provide signal strength measurements. The attenuators were used to insert initial threshold to avoid problems associated with non-linear S-meter readings, and with S-meter saturation in the presence of full squelch quieting.

Each antenna was quickly switched in for volt-ohmmeter measurement, with attenuation added or subtracted to obtain the same meter reading as experienced with the reference quad. All readings were corrected for SWR attenuation. For the reference quad, the SWR was 2.4:1 for 120Ω impedance, and for the fractal quad antennas SWR was less than 1.5:1 at resonance. The lack of a suitable noise bridge for 2 M precluded efficiency measurements for the various antennas. Understandably, anechoic chamber testing would provide even more useful measurements.

For each antenna, relative forward gain and optimized physical orientation were measured. No attempt was made to correct for launch-angle, or to measure power patterns other than to demonstrate the broadside nature of the gain. Difference of $1/2$ dB produced noticeable S-meter deflections, and differences of several dB produced

substantial meter deflection. Removal of the antenna from the receiver resulted in a 20⁺ dB drop in received signal strength. In this fashion, system distortions in readings were cancelled out to provide more meaningful results. Table 3 summarizes these results.

TABLE 3

Antenna	PC	PL	SWR	Cor. Gain (dB)	Sidelength (λ)
Quad	1	1	2.4:1	0	0.25
1/4 wave	1	--	1.5:1	-1.5	0.25
MI-1	1.3	1.2	1.3:1	1.5	0.13
MI-2	1.9	1.4	1.3:1	1.5	0.13
MI-3	2.4	1.7	1:1	-1.2	0.10

It is apparent from Table 3 that for the vertical configurations under test, a fractal quad according to the present invention either exceeded the gain of the prior art test quad, or had a gain deviation of not more than 1 dB from the test quad. Clearly, prior art cubical (square) quad antennas are not optimized for gain. Fractally shrinking a cubical quad by a factor of two will increase the gain, and further shrinking will exhibit modest losses of 1-2 dB.

Versions of a MI-2 and MI-3 fractal quad antennas were constructed for the 6 M (50 MHz) radio amateur band. An RX 50 Ω noise bridge was attached between these antennas and a transceiver. The receiver was nulled at about 54 MHz and the noise bridge was calibrated with 5 Ω and 10 Ω resistors. Table 4 below summarizes the results, in which almost no reactance was seen.

TABLE 4

Antenna	SWR	Z (Ω)	O (Ω)	E (%)
Quad (MI-0)	2.4:1	120	5-10	92-96
MI-2	1.2:1	60	≤ 5	≥ 92
MI-3	1.1:1	55	≤ 5	≥ 91

In Table 4, efficiency (E) was defined as $100\% \cdot (R/Z)$, where Z was the measured impedance, and R was Z minus ohmic impedance and reactive impedances (O). As shown in Table 4, fractal MI-2 and MI-3 antennas with their low $\leq 1.2:1$ SWR and low ohmic and reactive impedance provide extremely high efficiencies, 90+%. These findings are indeed surprising in view of prior art teachings stemming from early Euclidean small loop geometries. In fact, Table 4 strongly suggests that prior art associations of low radiation impedances for small loops must be abandoned in general, to be invoked only when discussing small Euclidean loops. Applicant's MI-3 antenna was indeed micro-sized, being dimensioned at about 0.1λ per side, an area of about $\lambda^2/1,000$, and yet did not signal the onset of inefficiency long thought to accompany smaller sized antennas.

However the 6M efficiency data do not explain the fact that the MI-3 fractal antenna had a gain drop of almost 3 dB relative to the MI-2 fractal antenna. The low ohmic impedances of $\leq 5 \Omega$ strongly suggest that the explanation is other than inefficiency, small antenna size notwithstanding. It is quite possible that near field diffraction effects occur at higher iterations that result in gain loss. However, the smaller antenna sizes achieved by higher iterations appear to warrant the small loss in gain.

Using fractal techniques, however, 2 M quad antennas dimensioned smaller than 3" (7.6 cm) on a side, as well

as 20 M (14 MHz) quads smaller than 3' (1 m) on a side
can be realized. Economically of greater interest,
fractal antennas constructed for cellular telephone
frequencies (850 MHz) could be sized smaller than 0.5"
5 (1.2 cm). As shown by Figures 8B and 8C, several such
antenna, each oriented differently could be fabricated
within the curved or rectilinear case of a cellular or
wireless telephone, with the antenna outputs coupled to a
circuit for coupling to the most optimally directed of
10 the antennas for the signal then being received. The
resultant antenna system would be smaller than the
"rubber-ducky" type antennas now used by cellular
telephones, but would have improved characteristics as
well.

15 Similarly, fractal-designed antennas could be used in
handheld military walkie-talkie transceivers, global
positioning systems, satellites, transponders, wireless
communication and computer networks, remote and/or
20 robotic control systems, among other applications.

Although the fractal Minkowski island antenna has been
described herein, other fractal motifs are also useful,
as well as non-island fractal configurations.

25 Table 5 demonstrates bandwidths ("BW") and multi-
frequency resonances of the MI-2 and MI-3 antennas
described, as well as Qs, for each node found for 6 M
versions between 30 MHz and 175 MHz. Irrespective of
30 resonant frequency SWR, the bandwidths shown are SWR 3:1
values. Q values shown were estimated by dividing
resonant frequency by the 3:1 SWR BW. Frequency ratio is
the relative scaling of resonance nodes.

TABLE 5

Antenna	Freq. (MHz)	Freq. Ratio	SWR	3:1 BW	Q
MI-3	53.0	1	1:1	6.4	8.3
	80.1	1.5:1	1.1:1	4.5	17.7
	121.0	2.3:1	2.4:1	6.8	17.7
MI-2	54.0	1	1:1	3.6	15.0
	95.8	1.8:1	1.1:1	7.3	13.1
	126.5	2.3:1	2.4:1	9.4	13.4

The Q values in Table 5 reflect that MI-2 and MI-3 fractal antennas are multiband. These antennas do not display the very high Qs seen in small tuned Euclidean loops, and there appears not to exist a mathematical application to electromagnetics for predicting these resonances or Qs. One approach might be to estimate scalar and vector potentials in Maxwell's equations by regarding each Minkowski Island iteration as a series of vertical and horizontal line segments with offset positions. Summation of these segments will lead to a Poynting vector calculation and power pattern that may be especially useful in better predicting fractal antenna characteristics and optimized shapes.

In practice, actual Minkowski Island fractal antennas seem to perform slightly better than their ELNEC predictions, most likely due to inconsistencies in ELNEC modelling or ratios of resonant frequencies, PCs, SWRs and gains.

Those skilled in the art will appreciate that fractal multiband antenna arrays may also be constructed. The resultant arrays will be smaller than their Euclidean counterparts, will present less wind area, and will be mechanically rotatable with a smaller antenna rotator.

Further, fractal antenna configurations using other than Minkowski islands or loops may be implemented. Table 6 shows the highest iteration number N for other fractal configurations that were found by applicant to resonant on at least one frequency.

TABLE 6

Fractal	Maximum Iteration
Koch	5
Torn Square	4
Minkowski	3
Mandelbrot	4
Caley Tree	4
Monkey's Swing	3
Sierpinski Gasket	3
Cantor Gasket	3

Figure 9A depicts gain relative to an Euclidean quad (e.g., an MI-0) configuration as a function of iteration value N. (It is understood that an Euclidean quad exhibits 1.5 dB gain relative to a standard reference dipole.) For first and second order iterations, the gain of a fractal quad increases relative to an Euclidean quad. However, beyond second order, gain drops off relative to an Euclidean quad. Applicant believes that near field electromagnetic energy diffraction-type cancellations may account for the gain loss for $N > 2$. Possibly the far smaller areas found in fractal antennas according to the present invention bring this diffraction phenomenon into sharper focus.

In practice, applicant could not physically bend wire for a 4th or 5th iteration 2 M Minkowski fractal antenna, although at lower frequencies the larger antenna sizes would not present this problem. However, at higher frequencies, printed circuitry techniques, semiconductor

fabrication techniques as well as machine-construction could readily produce $N=4$, $N=5$, and higher order iterations fractal antennas.

5 In practice, a Minkowski island fractal antenna should reach the theoretical gain limit of about 1.7 dB seen for sub-wavelength Euclidean loops, but N will be higher than 3. Conservatively, however, an $N=4$ Minkowski Island fractal quad antenna should provide a $PC=3$ value without
10 exhibiting substantial inefficiency.

Figure 9B depicts perimeter compression (PC) as a function of iteration order N for a Minkowski island fractal configuration. A conventional Euclidean quad
15 (MI-0) has $PC=1$ (e.g., no compression), and as iteration increases, PC increases. Note that as N increases and approaches 6, PC approaches a finite real number asymptotically, as predicted. Thus, fractal Minkowski Island antennas beyond iteration $N=6$ may exhibit
20 diminishing returns for the increase in iteration.

It will be appreciated that the non-harmonic resonant frequency characteristic of a fractal antenna according to the present invention may be used in a system in which
25 the frequency signature of the antenna must be recognized to pass a security test. For example, at suitably high frequencies, perhaps several hundred MHz, a fractal antenna could be implemented within an identification credit card. When the card is used, a transmitter
30 associated with a credit card reader can electronically sample the frequency resonance of the antenna within the credit card. If and only if the credit card antenna responds with the appropriate frequency signature pattern expected may the credit card be used, e.g., for purchase
35 or to permit the owner entrance into an otherwise secured area.

Figure 10A depicts a fractal inductor L according to the present invention. In contrast to a prior art inductor, the winding or traces with which L is fabricated define, at least in part, a fractal. The resultant inductor is physically smaller than its Euclidean counterpart.

Inductor L may be used to form a resonator, including resonators such as shown in Figures 4A and 4B. As such, an integrated circuit or other suitably small package including fractal resonators could be used as part of a security system in which electromagnetic radiation, perhaps from transmitter 600 or 660 in Figure 8A will blow, or perhaps not blow, an LC resonator circuit containing the fractal antenna. Such applications are described elsewhere herein and may include a credit card sized unit 700, as shown in Figure 10B, in which an LC fractal resonator 710 is implemented. (Card 700 is depicted in Figure 10B as though its upper surface were transparent.)

The foregoing description has largely replicated what has been set forth in applicant's above-noted FRACTAL ANTENNAS AND FRACTAL RESONATORS patent application. The following section will set forth methods and techniques for tuning such fractal antennas and resonators. In the following description, although the expression "antenna" may be used in referring to a preferably fractal element, in practice what is being described is an antenna or filter-resonator system. As such, an "antenna" can be made to behave as through it were a filter, e.g., passing certain frequencies and rejecting other frequencies (or the converse).

In one group of embodiments, applicant has discovered that disposing a fractal antenna a distance Δ that is in close proximity (e.g., less than about 0.05λ for the frequency of interest) from a conductor advantageously can change the resonant properties and radiation

characteristics of the antenna (relative to such properties and characteristics when such close proximity does not exist, e.g., when the spaced-apart distance is relatively great. For example, in Figure 11A a
5 conductive surface 800 is disposed a distance Δ behind or beneath a fractal antenna 810, which in Figure 11A is a single arm of an MI-2 fractal antenna. Of course other fractal configurations such as disclosed herein could be used instead of the MI-1 configuration shown, and non-
10 planar configurations may also be used. Fractal antenna 810 preferably is fed with coaxial cable feedline 50, whose center conductor is attached to one end 815 of the fractal antenna, and whose outer shield is grounded to the conductive plane 800. As described herein, great
15 flexibility in connecting the antenna system shown to a preferably coaxial feedline exists. Termination impedance is approximately of similar magnitudes as described earlier herein.

20 In the configuration shown, the relative close proximity between conductive sheet 800 and fractal antenna 810 lowers the resonant frequencies and widens the bandwidth of antenna 810. The conductive sheet 800 may be a plane of metal, the upper copper surface of a printed circuit
25 board, a region of conductive material perhaps sprayed onto the housing of a device employing the antenna, for example the interior of a transceiver housing 500, such as shown in Figures 8A, 8B, 8C, and 15.

30 The relationship between Δ , wherein $\Delta \leq 0.05\lambda$, and resonant properties and radiation characteristics of a fractal antenna system is generally logarithmic. That is, resonant frequency decreases logarithmically with decreasing separation Δ .

35

Figure 11B shows an embodiment in which a preferably fractal antenna 810 lies in the same plane as a ground

plane 800 but is separated therefrom by an insulating region, and in which a passive or parasitic element 800' is disposed "within" and spaced-apart a distance Δ' from the antenna, and also being coplanar. For example, the
5 embodiment of Figure 11B may be fabricated from a single piece of printed circuit board material in which copper (or other conductive material) remains to define the groundplane 800, the antenna 810, and the parasitic element 800', the remaining portions of the original
10 material having been etched away to form the "moat-like" regions separating regions 800, 810, and 800'. Changing the shape and/or size of element 800' and/or the coplanar spaced-apart distance Δ' tunes the antenna system shown. For example, for a center frequency in the 900 MHz range,
15 element 800' measured about 63 mm x 8 mm, and elements 810 and 800 each measured about 25 mm x 12 mm. In general, element 800 should be at least as large as the preferably fractal antenna 810. For this configuration, the system shown exhibited a bandwidth of about 200 MHz,
20 and could be made to exhibit characteristics of a bandpass filter and/or band rejection filter. In this embodiment, a coaxial feedline 50 was used, in which the center lead was coupled to antenna 810, and the ground shield lead was coupled to groundplane 800. In Figure
25 11B, the inner perimeter of groundplane region 800 is shown as being rectangularly shaped. If desired, this inner perimeter could be moved closer to the outer perimeter of preferably fractal antenna 810, and could in fact define a perimeter shape that follows the perimeter
30 shape of antenna 810. In such an embodiment, the perimeter of the inner conductive region 800' and the inner perimeter of the ground plane region 800 would each follow the shape of antenna 810. Based upon experiments to date, it is applicant's belief that moving the inner
35 perimeter of ground plane region 800 sufficiently close to antenna 810 could also affect the characteristics of the overall antenna/resonator system.

Referring now to Figure 12A, if the conductive surface 800 is replaced with a second fractal antenna 810', which is spaced-apart a distance Δ that preferably does not exceed about 0.05λ , resonances for the radiating fractal antenna 810 are lowered and advantageously new resonant frequencies emerge. For ease of fabrication, it may be desired to construct antenna 810 on the upper or first surface 820A of a substrate 820, and to construct antenna 810' on the lower or second surface 820B of the same substrate. The substrate could be doubled-side printed circuit board type material, if desired, wherein antennas 810, 810' are fabricated using printed circuit type techniques. The substrate thickness Δ is selected to provide the desired performance for antenna 810 at the frequency of interest. Substrate 820 may, for example, be a non-conductive film, flexible or otherwise. To avoid cluttering Figures 12A and 12B, substrate 820 is drawn with phantom lines, as if the substrate were transparent.

Preferably, the center conductor of coaxial cable 50 is connected to one end 815 of antenna 810, and the outer conductor of cable 50 is connected to a free end 815' of antenna 810', which is regarded as ground, although other feedline connections may be used. Although Figure 12A depicts antenna 810' as being substantially identical to antenna 810, the two antennas could in fact have different configurations.

Applicant has discovered that if the second antenna 810' is rotated some angle θ relative to antenna 810, the resonant frequencies of antenna 810 may be varied, analogously to tuning a variable capacitor. Thus, in Figure 12B, antenna 810 is tuned by rotating antenna 810' relative to antenna 810 (or the converse, or by rotating each antenna). If desired, substrate 820 could comprise two substrates each having thickness $\Delta/2$ and pivotally

connected together, e.g., with a non-conductive rivet, so as to permit rotation of the substrates and thus relative rotation of the two antennas. Those skilled in the mechanical arts will appreciate that a variety of

5 "tuning" mechanisms could be implemented to permit fine control over the angle θ in response, for example, to rotation of a tunable shaft.

Referring now to Figure 13A, applicant has discovered

10 that creating at least one cut or opening 830 in a fractal antenna 810 (here comprising two legs of an MI-2 antenna) results in new and entirely different resonant nodes for the antenna. Further, these nodes can have perimeter compression (PC) ranging from perhaps three to

15 about ten. The precise location of cut 830 on the fractal antenna or resonator does not appear to be critical.

Figures 13B and 13C depict a self-proximity

20 characteristic of fractal antennas and resonators that may advantageously be used to create a desired frequency resonant shift. In Figure 13B, a fractal antenna 810 is fabricated on a first surface 820A of a flexible substrate 820, whose second surface 820B does not contain

25 an antenna or other conductor in this embodiment. Curving substrate 820, which may be a flexible film, appears to cause electromagnetic fields associated with antenna 810 to be sufficiently in self-proximity so as to shift resonant frequencies. Such self-proximity antennas

30 or resonators may be referred to as com-cyl devices. The extent of curvature may be controlled where a flexible substrate or substrate-less fractal antenna and/or conductive element is present, to control or tune frequency dependent characteristics of the resultant

35 system. Com-cyl embodiments could include a concentrically or eccentrically disposed fractal antenna and conductive element. Such embodiments may include

telescopic elements, whose extent of "overlap" may be telescopically adjusted by contracting or lengthening the overall configuration to tune the characteristics of the resultant system. Further, more than two elements could be provided.

In Figure 13C, a fractal antenna 810 is formed on the outer surface 820A of a filled substrate 820, which may be a ferrite core. The resultant com-cyl antenna appears to exhibit self-proximity such that desired shifts in resonant frequency are produced. The geometry of the core 820, e.g., the extent of curvature (e.g., radius in this embodiment) relative to the size of antenna 810 may be used to determine frequency shifts.

In Figure 14A, an antenna or resonator system is shown in which the non-driven fractal antenna 810' is not connected to the preferably coaxial feedline 50. The ground shield portion of feedline 50 is coupled to the groundplane conductive element 800, but is not otherwise connected to a system ground. Of course fractal antenna 810' could be angularly rotated relative to driven antenna 810, it could be a different configuration than antenna 810 including having a different iteration N, and indeed could incorporate other features disclosed herein (e.g., a cut).

Figure 14B demonstrates that the driven antenna 810 may be coupled to the feedline 50 at any point 815', and not necessarily at an end point 8'5 as was shown in Figure 14A.

In the embodiment of Figure 14C, a second ground plane element 800' is disposed adjacent at least a portion of the system comprising driven antenna 810, passive antenna 810', and the underlying conductive planar element 800. The presence, location, geometry, and distance associated

with second ground plane element 800' from the underlying elements 810, 810', 800 permit tuning characteristics of the overall antenna or resonator system. In the multi-element sandwich-like configuration shown, the ground shield of conductor 50 is connected to a system ground but not to either ground plane 800 or 800'. Of course more than three elements could be used to form a tunable system according to the present invention.

Figure 14D shows a single fractal antenna spaced apart from an underlying ground plane 800 a distance Δ , in which a region of antenna 800 is cutaway to increase resonance. In Figure 14D, for example, L1 denotes a cutline, denoting that portions of antenna 810 above (in the Figure drawn) L1 are cutaway and removed. So doing will increase the frequencies of resonance associated with the remaining antenna or resonator system. On the other hand, if portions of antenna 810 above cutline L2 are cutaway and removed, still higher resonances will result. Selectively cutting or etching away portions of antenna 810 permit tuning characteristics of the remaining system.

Figure 15 depicts an embodiment somewhat similar to what has been described with respect to Figure 8B or Figure 8C. Once again unit 500 is a handheld transceiver, and includes fractal antennas 510A, 510B-510B', 510C. Antennas 510B-510B' are similar to what has been described with respect to Figures 12A-12B. Antennas 510B-510B' are fractal antennas, not necessarily MI-2 configuration as shown, and are spaced-apart a distance Δ and, in Figure 13, are rotationally displaced. Collectively, the spaced-apart distance and relative rotational displacement permits tuning the characteristics of the driven antenna, here antenna 510B. In Figure 14, antenna 510A is drawn with phantom lines to better distinguish it from spaced-apart antenna 510B. Of

course passive conductor 510B' could instead be a solid conductor such as described with respect to Figure 11A. Such conductor may be implemented by spraying the inner surface of the housing for unit 500 adjacent antenna 510B
5 with conductive paint.

In Figure 13, antenna 510C is similar to what has been described with respect to Figure 13A, in that a cut 830 is made in the antenna, for tuning purposes. Although
10 antenna 510A is shown similar to what was shown in Figure 8B, antenna 510A could, if desired, be formed on a curved substrate similar to Figures 13B or 13C. While Figure 13 shows at least two different techniques for tuning
15 antennas according to the present invention, it will be understood that a common technique could instead be used. By that it is meant that any or all of antennas 510A, 510B-510B', 510C could include a cut, or be spaced-apart a controllable distance Δ , or be rotatable relative to a spaced-apart conductor.

As described with respect to Figure 8B, an electronic circuit 610 may be coupled by cables 50A, 50B, 50C to the antennas, and samples incoming signals to discern which
20 fractal antenna, e.g., 510A, 510B-510B', 510C is presently most optimally aligned with the transmitting station, perhaps a unit 600 or 650 or 670 as shown in Figure 8A. This determination may be made by examining
25 signal strength from each of the antennas. An electronic circuit 620 then selects the presently best oriented antenna, and couples such antenna to the input of the receiver and output of the transmitter portion,
30 collectively 630, of unit 500. It is understood that the selection of the best antenna is dynamic and can change as, for example, a user of 500 perhaps walks about
35 holding the unit, or the transmitting source moves, or due to other changing conditions. In a cellular or a wireless telephone application, the result is more

reliable communication, with the advantage that the fractal antennas can be sufficiently small-sized as to fit totally within the casing of unit 500. Further, if a flexible substrate is used, the antennas may be wrapped about portions of the internal casing, as shown.

An additional advantage of the embodiment of Figure 8B is that the user of unit 500 may be physically distanced from the antennas by a greater distance than if a conventional external whip antenna were used. Although medical evidence attempting to link cancer with exposure to electromagnetic radiation from handheld transceivers is still inconclusive, the embodiment of Figure 8B appears to minimize any such risk.

Modifications and variations may be made to the disclosed embodiments without departing from the subject and spirit of the invention as defined by the following claims. While common fractal families include Koch, Minkowski, Julia, diffusion limited aggregates, fractal trees, Mandelbrot, the present invention may be practiced with other fractals as well.